

Neutrino spin and spin-flavour oscillations in transversally moving or polarized matter

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Abstract.

Studies of an interesting effect of neutrino spin and spin-flavour oscillations engenders by neutrino weak interactions with the transversally moving or polarized matter are reviewed.

It is well known that massive neutrinos have nontrivial electromagnetic properties, and at least the magnetic moment is not zero [1]. Thus, neutrinos do participate also in the electromagnetic interaction (see [2] for a review). The best terrestrial laboratory upper bound on neutrino magnetic moments is obtained by the GEMMA reactor neutrino experiment [3]. The best astrophysical upper bound was derived from considering stars cooling [4]. The neutrino magnetic moment precession in the transversal magnetic field \mathbf{B}_\perp was first considered in [5], then spin-flavor precession in vacuum was discussed in [6], the importance of the matter effect was emphasized in [7]. The effect of resonant amplification of neutrino spin oscillations in \mathbf{B}_\perp in the presence of matter was proposed in [8, 9], the impact of the longitudinal magnetic field \mathbf{B}_\parallel was discussed in [10]. Recently we consider in details [11] neutrino mixing and oscillations in arbitrary constant magnetic field that have \mathbf{B}_\perp and \mathbf{B}_\parallel nonzero components in mass and flavour bases. We have also developed a new (and more precise than the usual one) approach to description of neutrino spin and spin-flavor oscillations in the presence of an arbitrary magnetic field [13]. Our approach is based on the use of the stationary states in the magnetic field for classification of neutrino spin states, contrary to the customary approach when the neutrino helicity states are used for this purpose.

In this short note we focus on a very interesting effect in neutrino spin and spin-flavour oscillations in presence of matter background that was first discussed in our paper [14]. In our studies it was shown that neutrino spin and spin-flavour oscillations can be induced not only by the neutrino interaction with a magnetic field, as it was believed before, but also by neutrino interactions with matter in the case when there is a transversal matter current or matter polarization. In the Conclusions of [14] one finds:

“The possible emergence of neutrino spin oscillations owing to neutrino interaction with matter under the condition that there exists a nonzero transverse current component or matter polarization is the most important new effect that follows from the investigation of neutrino-spin oscillations in Section 4. So far, it has been assumed that neutrino-spin oscillations may arise only in the case where there exists a nonzero transverse magnetic field in the neutrino rest frame.”

It should be noted that the predicted effect exist regardless of a source of the background matter transversal current or polarization (that can be a background magnetic field, for instance).

Note that the existence of the discussed effect of neutrino spin oscillations engendered by the transversal matter current and matter polarization and its importance for astrophysical applications have been confirmed in a series of recent papers [19, 20, 21, 22].

Consider, as an example, an electron neutrino spin precession in the case when neutrinos with the Standard Model interaction are propagating through moving and polarized matter composed of electrons (electron gas) in the presence of an electromagnetic field given by the electromagnetic-field tensor $F_{\mu\nu} = (\mathbf{E}, \mathbf{B})$. As discussed in [14, 15] (see also [16, 17, 18]), the generalized Bargmann-Michel-Telegdi equation describes the evolution of the three-dimensional neutrino spin vector \vec{S} ,

$$\frac{d\mathbf{S}}{dt} = \frac{2\mu}{\gamma} \left[\mathbf{S} \times (\mathbf{B}_0 + \mathbf{M}_0) \right], \quad (1)$$

where the magnetic field \mathbf{B}_0 in the neutrino rest frame is determined by the transversal and longitudinal (with respect to the neutrino motion) magnetic and electric field components in the laboratory frame,

$$\mathbf{B}_0 = \gamma \left(\mathbf{B}_\perp + \frac{1}{\gamma} \mathbf{B}_\parallel + \sqrt{1 - \gamma^{-2}} \left[\mathbf{E}_\perp \times \frac{\boldsymbol{\beta}}{\beta} \right] \right), \quad (2)$$

$\gamma = (1 - \beta^2)^{-\frac{1}{2}}$, $\boldsymbol{\beta}$ is the neutrino velocity.

The matter term \mathbf{M}_0 in Eq. (1) is also composed of the transversal $\mathbf{M}_{0\parallel}$ and longitudinal $\mathbf{M}_{0\perp}$ parts,

$$\mathbf{M}_0 = \mathbf{M}_{0\parallel} + \mathbf{M}_{0\perp}, \quad (3)$$

$$\mathbf{M}_{0\parallel} = \gamma\beta \frac{n_0}{\sqrt{1 - v_e^2}} \left\{ \rho_e^{(1)} \left(1 - \frac{\mathbf{v}_e \boldsymbol{\beta}}{1 - \gamma^{-2}} \right) \right\} - \frac{\rho_e^{(2)}}{1 - \gamma^{-2}} \left\{ \zeta_e \beta \sqrt{1 - v_e^2} + \left(\zeta_e \mathbf{v}_e \frac{(\boldsymbol{\beta} \mathbf{v}_e)}{1 + \sqrt{1 - v_e^2}} \right) \right\}, \quad (4)$$

$$\mathbf{M}_{0\perp} = -\frac{n_0}{\sqrt{1 - v_e^2}} \left\{ \mathbf{v}_{e\perp} \left(\rho_e^{(1)} + \rho_e^{(2)} \frac{(\zeta_e \mathbf{v}_e)}{1 + \sqrt{1 - v_e^2}} \right) + \zeta_{e\perp} \rho_e^{(2)} \sqrt{1 - v_e^2} \right\}. \quad (5)$$

Here $n_0 = n_e \sqrt{1 - v_e^2}$ is the invariant number density of matter given in the reference frame for which the total speed of matter is zero. The vectors \mathbf{v}_e , and ζ_e ($0 \leq |\zeta_e|^2 \leq 1$) denote, respectively, the speed of the reference frame in which the mean momentum of matter (electrons) is zero, and the mean value of the polarization vector of the background electrons in the above mentioned reference frame. The coefficients $\rho_e^{(1,2)}$ calculated within the extended Standard Model supplied with $SU(2)$ -singlet right-handed neutrino ν_R are respectively, $\rho_e^{(1)} = \frac{\tilde{G}_F}{2\sqrt{2}\mu}$, $\rho_e^{(2)} = -\frac{G_F}{2\sqrt{2}\mu}$, where $\tilde{G}_F = G_F(1 + 4 \sin^2 \theta_W)$.

For neutrino evolution between two neutrino states $\nu_e^L \Leftrightarrow \nu_e^R$ in presence of the magnetic field and moving matter we get [14] the following equation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e^L \\ \nu_e^R \end{pmatrix} = \mu \begin{pmatrix} \frac{1}{\gamma} |\mathbf{M}_{0\parallel} + \mathbf{B}_{0\parallel}| & |\mathbf{B}_\perp + \frac{1}{\gamma} \mathbf{M}_{0\perp}| \\ |\mathbf{B}_\perp + \frac{1}{\gamma} \mathbf{M}_{0\perp}| & -\frac{1}{\gamma} |\mathbf{M}_{0\parallel} + \mathbf{B}_{0\parallel}| \end{pmatrix} \begin{pmatrix} \nu_e^L \\ \nu_e^R \end{pmatrix}. \quad (6)$$

Thus, the probability of the neutrino spin oscillations in the adiabatic approximation is given by (see [14, 15])

$$P_{\nu_L \rightarrow \nu_R}(x) = \sin^2 2\theta_{\text{eff}} \sin^2 \frac{\pi x}{L_{\text{eff}}}, \quad \sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad L_{\text{eff}} = \frac{2\pi}{\sqrt{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}}, \quad (7)$$

where

$$E_{\text{eff}} = \mu |\mathbf{B}_{\perp} + \frac{1}{\gamma} \mathbf{M}_{0\perp}|, \quad \Delta_{\text{eff}} = \frac{\mu}{\gamma} |\mathbf{M}_{0\parallel} + \mathbf{B}_{0\parallel}|. \quad (8)$$

Thus, it follows that even without presence of an electromagnetic field, $\mathbf{B}_{\perp} = \mathbf{B}_{0\parallel} = 0$, neutrino spin oscillations can be induced in the presence of matter when the transverse matter term $\mathbf{M}_{0\perp}$ is not zero. This possibility is realized in the case when the transverse component of the background matter velocity or its transverse polarization is not zero.

The above considerations can be applied to other types of neutrinos and various matter compositions. It is also obvious that for neutrinos with nonzero transition magnetic moments a similar effect of spin-flavour oscillations exists under the same background conditions.

The possibility of neutrino spin precession and oscillations induced by the transversal matter current or polarization was first discussed in [14, 15]. More general case of neutrino spin evolution in the case when neutrino is subjected to general types of non-derivative interactions with external scalar s , pseudoscalar π , vector V_{μ} , axial-vector A_{μ} , tensor $T_{\mu\nu}$ and pseudotensor $\Pi_{\mu\nu}$ fields was considered in [18]. From the obtained general neutrino spin evolution equation it follows that neither scalar s nor pseudoscalar π nor vector V_{μ} fields can induce neutrino spin evolution. On the contrary, within the general consideration of neutrino spin evolution it was shown that electromagnetic (tensor) and weak (axial-vector) interactions can contribute to the neutrino spin evolution.

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